The Effects of Changes in Utilization and Technological Advancements of Cross-Sectional Imaging on Radiologist Workload

Robert J. McDonald, MD, PhD, Kara M. Schwartz, MD, Laurence J. Eckel, MD, Felix E. Diehn, MD, Christopher H. Hunt, MD, Brian J. Bartholmai, MD, Bradley J. Erickson, MD, PhD, David F. Kallmes, MD

Rationale and Objectives: To examine the effect of changes in utilization and advances in cross-sectional imaging on radiologists' workload.

Materials and Methods: All computed tomography (CT) and magnetic resonance imaging (MRI) examinations performed at a single institution between 1999 and 2010 were identified and associated with the total number of images for each examination. Annual trends in institutional numbers of interpreted examinations and images were translated to changes in daily workload for the individual radiologist by normalizing to the number of dedicated daily CT and MRI work assignments, assuming a 255-day/8-hour work day schedule. Temporal changes in institutional and individual workload were assessed by Sen's slope analysis (Q = median slope) and Mann–Kendall test (Z = Z statistic).

Results: From 1999 to 2010, a total of 1,517,149 cross-sectional imaging studies (CT = 994,471; MRI = 522,678) comprising 539,210,581 images (CT = 339,830,947; MRI = 199,379,634) were evaluated at our institution. Total annual cross-sectional studies steadily increased from 84,409 in 1999 to 147,336 in 2010, representing a twofold increase in workload (Q = 6465/year, Z = 4.2, $P < .0001$). Concomitantly, the number of annual departmental cross-sectional images interpreted increased from 9,294,140 in 1990 to 94,271,551 in 2010, representing a 10-fold increase (Q = 8707876/year, Z = 4.5, $P < .0001$). Adjusting for staffing changes, the number of images requiring interpretation per minute of every workday per staff radiologist increased from 2.9 in 1999 to 16.1 in 2010 (Q = 1.7/year, Z = 4.3, $P < .0001$).

Conclusions: Imaging volumes have grown at a disproportionate rate to imaging utilization increases at our institution. The average radiologist interpreting CT or MRI examinations must now interpret one image every 3–4 seconds in an 8-hour workday to meet workload demands.

Key Words: Cross-sectional imaging; imaging volumes; utilization; workload; fatigue.

Over the past decade, advanced cross-sectional imaging utilization has been rapidly increasing (1–4). Fueled by technical innovations that have improved the anatomic resolution, sensitivity, and specificity of computed tomography (CT) and magnetic resonance imaging (MRI) modalities, medical practice has evolved to heavily rely on these imaging techniques over older, conventional radiographic imaging modalities (5–9). Indeed, many clinical practice guidelines, particularly in the emergent setting, have supplanted conventional radiography with CT and MRI examinations as the key elements in their clinical decision-making algorithm (4). Much of this evolution has been driven by evidence-based medicine of the superiority of cross-sectional imaging over conventional radiography in the accurate detection of disease (4,10–19). Advances in multidetector CT, dual-source CT, gradient-based MR pulse sequences, and novel pulse sequences have also greatly diminished the acquisition time of these studies, permitting a higher-throughput model of health care delivery (2,3,5,20–22).

As imaging reimbursements decline, health care providers are being forced to compensate by increasing their productivity (2,3). Although the information technology infrastructure of radiology has evolved to meet the demands of higher imaging volumes vis-a-vis improved computational power, storage capacity, and workflow efficiency in the picture archiving and communication system (PACS) environment,

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From the Clinician Investigator Training Program, College of Medicine, Mayo Clinic, 200 1st St SW, Rochester, MN 55905 (R.J.M.); Department of Radiology, College of Medicine, Mayo Clinic, 200 1st St SW, Rochester, MN 55905 (R.J.M., K.M.S., L.J.E., F.E.D., C.H.H., B.J.B., B.J.E., D.F.K.); and Department of Neurosurgery, College of Medicine, Mayo Clinic, Rochester, Minnesota (D.F.K.) Received January 13, 2015; accepted May 18, 2015. **Address correspondence to:** R J. M. e-mail: mcdonald.robert@mayo.edu

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the amount of information (images) generated per examination has also substantially increased as a result of the technological advances noted previously (23–25). In turn, the modern radiologist must now interpret many times more examination images when compared to similar examinations performed 10–20 years ago. Although these advances in sensitivity and specificity are thought to translate to improved patient care, these increasing imaging volumes are placing an ever-increasing burden on the practicing radiologist (26,27). As the workload continues to increase, there is concern that the quality of the health care delivered by the radiologist will decline in the form of increased detection errors as a result of increased fatigue and stress (28,29). As errors in the interpretation of radiologic images can be associated with catastrophic clinical outcomes, such concerns are tantamount to patient safety.

In the present study, we sought to identify trends in utilization of cross-sectional modalities (CT and MRI) at our medical institution to determine changes in utilization, information creation, and radiologist workload over time.

MATERIALS AND METHODS

Study Design

This retrospective study performed at a single academic medical center met Health Insurance Portability and Accountability Act privacy guidelines and was subject to institutional review board (IRB) approval. The need for continued IRB oversight was waived as this study qualified as a quality improvement project. All diagnostic, angiographic, and interventional CT and MRI examinations performed from 1999 to 2010 were extracted from our institutional Radiology Information Management System using current procedural terminology (CPT) codes. In addition to examination details, study date, indication, interpreting radiologist, and numbers of images per study were extracted from the same Radiology Information Management System CPT-driven search.

Study Grouping

Imaging examinations were grouped based on modality (CT vs. MRI), type (diagnostic, angiographic [cardiac or vascular examinations], or interventional [examinations performed during biopsies, drain placement]), and subspecialty. Subspecialty grouping was based on institutional practices in the distribution of workload between departmental divisions and subspecialists as follows: neuro (head, brain, spine, and neck examinations), vascular (cardiac and CT/MR angiographic examinations; exclusive of CTA and MRA of the head and neck), chest (thoracic examinations exclusive of cardiac and vascular studies), body (all abdominal and pelvic [soft tissue] imaging examinations), musculoskeletal (MSK: extremity, joint, and pelvic [bone] imaging exclusive of spine examinations), gastrointestinal (GI: dedicated gastrointestinal examinations including CT/MR enterography and colonoscopy), genitourinary (GU: renal and genitourinary system examinations). Combined examination reports involving multiple anatomic locations (eg, chest, abdomen, and pelvis) were treated as a single examination when interpreted by the same radiologist; a common practice at our institution.

Departmental Staffing/Practice Patterns

Daily interpretation duties at our institution have historically been divided by modality, study type, and subspecialty into separate work assignments (worklines) that are filled by one of our staff radiologists. For example, a staff radiologist assigned to a daily CT workline is solely responsible for reading CT examinations of a specific subspecialty but may be assigned to a different workline the following workday. Furthermore, radiologists assigned to a CT or MRI workline at our institution are not asked to interpret other modalities (plain film, ultrasound, fluoroscopy) during the normal work day as these other studies are interpreted by separate worklines/staff radiologists. Archived staffing schedules were retrieved to track changes in the number of dedicated CT and MRI worklines over the study interval. During the entire study period, staff radiologists had between 5-37 years experience interpreting CT examinations and between 5 and 31 years' experience interpreting MRI examinations.

Departmental Imaging and Data Storage Policies

For CT examinations, all images interpreted and stored on PACS are derived from reconstructions of the primary isotropic data. In contradistinction to imaging centers where reconstructions are generated by the interpreting radiologists from thin-section data sent to PACS, images sent to PACS at our institution are generated for the prescribed planes, slice thicknesses, and reconstruction kernels (eg, bone, soft tissue) deemed necessary for a specific imaging protocol. Thin-section series are included only when deemed necessary such as in cases of suspected trauma, musculoskeletal examinations, and vascular examinations. MRI examination images are similarly protocol specific at our institution, and only the prescribed images/series in a given imaging protocol are sent to PACS for interpretation. Our department completely transitioned to filmless image interpretation in 2004 using a combination of Siemens and GE PACS systems. Before this date, CT and MRI images were interpreted using PACS (Siemens or GE) for all cross-sectional studies with the exception of neuroradiology examinations that were interpreted on printed film.

Outcomes

The primary outcomes of interest for this study included 1) the total number of CT and MRI examinations interpreted per year, 2) the total number of exam images interpreted per year, 3) the number of exams and images interpreted per assigned staff workline per year, and 4) the number of images interpreted per minute per staff workline, normalized to a 255-day work-year and uninterrupted 8-hour workday. The latter two outcomes were used to define the imaging workload of the individual radiologist.

Statistical Analysis

Statistical analyses were performed by R.J.M. using R [version 3.01, R Foundation for Statistical Computing, Vienna, Austria (30)]. Changes in CT and MRI examination utilization and content (number of images) over time were assessed using the Mann–Kendall test (Z) and Sen's slope estimator (Q) using the R package wq (version 0.3-11). These robust nonparametric linear regression tests assess for the presence of a significant positive or negative monotonic trend (Z) and median slope (Q). Such methods are commonly used in the physical sciences to estimate change over time as they are far less sensitive to outliers than traditional regression methods (31,32). Graphics were generated using the R package ggplot2 (version 0.9.3.1) (33). All tests of significance were two sided; significance was assigned where $P < .05$.

RESULTS

Trends in Number of Examinations Over Time

From 1999 to 2010, a total of 1,517,149 examinations (994,471 CT, 522,678 MRI) were performed at our institution. Trends in institutional CT and MRI examination utilization from 1999 to 2010 are shown in Figure 1a; Sen's slope estimates are summarized in Table 1. Over this span of time, CT examination utilization increased from 55,372 exams/year to 93,491 exams/year (Q = +4499 exams/year, $Z = 3.77$, $P < .0001$); representing a 68% increase in CT utilization over the study period. Similarly, MRI examination utilization also increased from 29,037 exams/year to 53,845 exams/year (Q = +2215 exams/year, $Z = 4.46$, $P < .0001$), representing an 85% increase in MRI utilization over the study period. Combined CT and MRI utilization increased from 84,409 exams/year to 147,336 exams/year (Q = +6464 exams/year, $Z = 4.18$, $P < .0001$), representing a 75% increase in imaging utilization over the study period.

Trends in Number of Images per Examination

From 1999 to 2010, a total of 539,210,581 images (339,830,947 CT, 199,379,634 MRI) were collected from CT and MRI examinations performed at our institution. Trends in total number of images and average number of images per examination collected from CT and MRI modalities are shown in Figures 1b and c, respectively; Sen's slope estimates are summarized in Table 1. Over this span of time, the number of CT-acquired images increased 1300% from 4,532,973 in 1999 to 63,565,174 in 2010 (Q = +6,112,616 images/year, $Z = 4.46$, $P < .0001$). The number of MRI-acquired images increased 540%, from 4,761,347 in

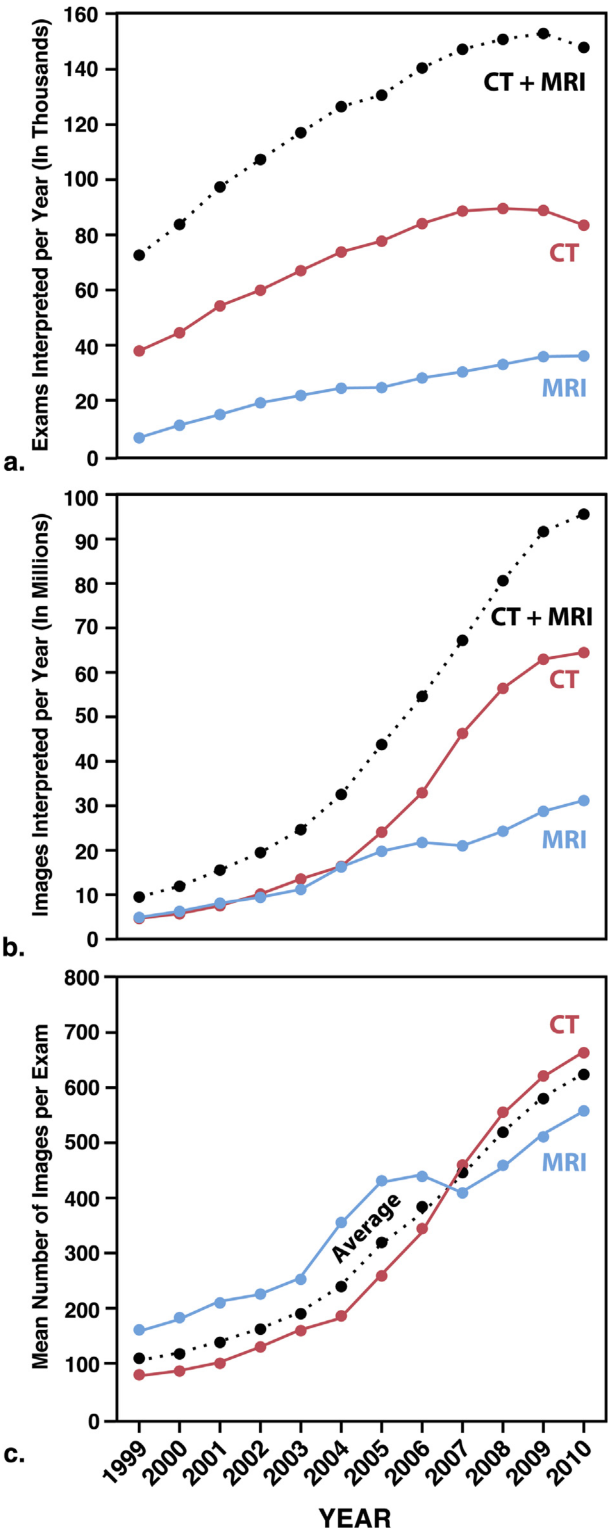


Figure 1. Imaging utilization trends for CT and MRI studies (1999–2010). Trends in annual numbers of interpreted exams **(a)**, interpreted images **(b)**, and average numbers of images per examination **(c)** are shown for CT and MRI modalities. CT data are shown as *blue lines* and MRI data are shown as *red lines*. Total numbers of examinations, images, and an average number of images collected per examination are shown as a *black dashed line*. CT, computed tomography; MRI, magnetic resonance imaging. (Color version of figure is available online.)

TABLE 1. Trends Over Time in Radiologist's Workloads

Type	Change Per Year	
	Median Change (95% CI)*	*P* Value
Total examinations interpreted/year		
CT	4499 (3218 to 5317)	<.0001
MRI	2215 (1885 to 2408)	<.0001
CT + MRI	6464 (5069 to 7885)	<.0001
Total images interpreted/year		
CT	6,112,616 (8,160,952 to 3,870,723)	<.0001
MRI	2,401,985 (2,868,584 to 2,051,647)	<.0001
CT + MRI	8,707,876 (8,160,952 to 10,993,169)	<.0001
Mean number of images/study		
CT	59 (39 to 78)	<.0001
MRI	38 (29 to 45)	<.0001
CT + MRI	54 (43 to 63)	<.0001
Number of worklines†		
CT	1.2 (0.9 to 1.3)	<.001
MRI	0.3 (−0.1 to 0.6)	.08
Examinations interpreted/year/workline†		
CT	−86 (−170 to 12)	.04
MRI	76 (21 to 135)	.01
CT + MRI	18 (−75 to 70)	.32
Images interpreted/year/workline†		
CT	214,873 (164,376 to 249,607)	<.0001
MRI	107,145 (74,876 to 134,855)	<.0001
CT + MRI	179,071 (152,309 to 199,931)	<.0001
Images interpreted/minute		
CT	1.8 (1.34 to 2.04)	<.0001
MRI	0.9 (0.61 to 1.01)	<.0001
CT + MRI	1.5 (1.24 to 1.63)	<.0001

CI, confidence interval; CT, computed tomography; MRI, magnetic resonance imaging.

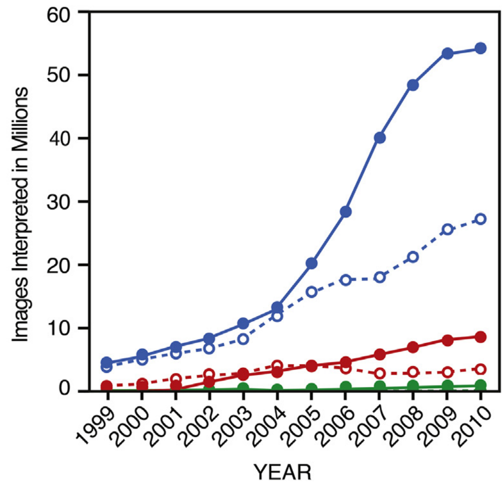
*Change per year (slope of the trend line) analyzed using Sen's slope analysis (*Q*). Significant *Z* values are reflected as positive or negative (−) trends for significant Q values.

†Workline is defined as the modality-specific daily work assignment for the radiologist. Day to day, the number of worklines are fixed and divided between modalities. For example, a radiologist assigned to a specific CT workline is responsible only for reading CT examinations that day.

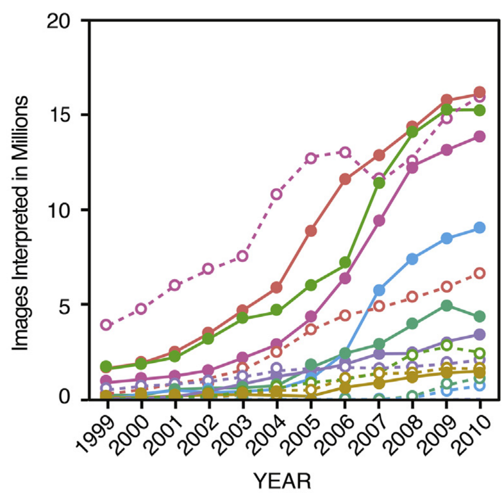
1999 to 30,706,377 in 2010 (Q = +2,401,985 images/year, $Z = 4.32$, $P < .0001$). When normalized for the number of images contained within each examination, the average CT examination grew from 82 images/examination in 1999 to 679 images/examination in 2010 (Q = +59 images/exam per year, $Z = 4.46$, $P < .0001$). MR examinations also increased from 164 images/examination in 1999 to 570 images/examination in 2010 (Q = +38 images/exam per year, $Z = 4.18$, $P < .0001$).

Imaging Trends by Examination Type and Subspecialty

The breakdown of interpreted CT and MRI examinations by type and subspecialty are shown in Figures 2a and b, respectively. From 1999 to 2010, diagnostic CT and MRI examinations were primarily responsible for the observed increases in image numbers (CT: Q = +4,974,252 images/year, $Z = 4.46$, $P < .0001$; MRI: Q = +2,235,791 images/year, $Z = 4.46$, $P < .0001$); CT and MR angiographic examination content also experienced modest growth over the study period (CT: Q = +866,537 images/year, $Z = 4.46$, $P < .0001$; MRI: Q = +215,688 images/year, $Z = 2.40$, $P = .0164$). In contrast, interventional examinations comprised a very small fraction of the annual number of interpreted images and utilization changed very little over the study period (CT: Q = +66,250 images/year, $Z = 3.63$, $P = .0004$; MRI: Q = +6894 images/year, $Z = 3.22$, $P = .0013$). Among CT examinations, neuro, body, and chest studies were the predominant contributors to the observed increases in imaging workload and demonstrated the greatest increases in number of interpreted images over the study period (Fig 2b). Collectively, these three modalities comprised 75.3% (255,878,286 of 339,830,947) of the total number of interpreted images over the study period. Among MRI examinations, neurostudies alone accounted for 60.7% (120,940,514 of 199,374,634) of the total number of interpreted images over the study period and were thus the predominant contributor to the observed increases in imaging workload.



	CT —— Q	CT —— p	MRI ---- Q	MRI ---- p
Diagnostic	50 x 10^6	<.0001	22 x 10^6	<.0001
Angiography	9 x 10^6	<.0001	2 x 10^6	.0164
a Interventional	6 x 10^5	.0004	7 x 10^4	.0013



	CT —— Q	CT —— p	MRI ---- Q	MRI ---- p
Neuro	13 x 10^6	<.0001	11 x 10^6	<.0001
Body	14 x 10^6	<.0001	6 x 10^6	<.0001
Chest	13 x 10^6	<.0001	2 x 10^6	<.0001
GU	9 x 10^6	<.0001	3 x 10^6	.0011
GI	4 x 10^6	<.0001	5 x 10^6	.0018
MSK	3 x 10^6	<.0001	1 x 10^6	<.0001
b Cardiac	1 x 10^6	<.0001	2 x 10^6	<.0001

Figure 2. Imaging utilization by examination type and subspecialty. **(a)** Trends in annual numbers of CT (*solid lines*) and MRI (*dashed lines*) images, sorted by type of examination (angiographic studies [*red lines*], diagnostic studies [*blue lines*], interventional studies [*green lines*]). **(b)** Trends in annual numbers of CT (*solid lines*) and MRI (*dashed lines*) images, sorted by subspecialty. Tabular displays of the average change in the annual number of interpreted images (Sen's slope [*Q*]) and the associated *P* value are shown for each modality–examination type and modality–subspecialty combination. CT, computed tomography; MRI, magnetic resonance imaging. (Color version of figure is available online.)

Trends in Radiologist Workload Over Time

From 1999 to 2010, the number of dedicated CT worklines increased from 13 to 27; dedicated MRI worklines increased over this same interval from 13 to 21 (Fig 3a). These changes were implemented based on departmental responses to changes in institutional imaging utilization. Accounting for changes in staffing, the average annual number of interpreted CT examinations for each workline modestly decreased and the average annual number of interpreted MRI examinations modestly increased over the study period (Fig 3b and Table 1; CT: $Q = -87$ annual exams/workline, $Z = -1.71$, $P = .04$; MRI: $+Q = 76$ annual exams/workline, $Z = 2.26$, $P = .01$). Similarly, the average annual number of interpreted images for each workline increased for both modalities (Fig 3c and Table 1; CT: $Q = +214{,}873$ annual images/workline, $Z = 4.32$, $P < .0001$; MRI: $Q = +107{,}145$ annual images/workline, $Z = 4.32$, $P < .0001$). Normalized to an uninterrupted 8-hour workday, the average number of images requiring interpretation per minute of every workday per staff radiologist increased nearly sevenfold from 2.8 in 1999 to 19.2 in 2010 for CT worklines and fourfold from 3.0 in 1999 to 11.9 in 2010 for MRI worklines (Fig 3d and Table 1; CT: $Q = +1.8$ images/min/year, $Z = 4.32$, $P < .0001$; MRI: $Q = +0.9$ images/min/year, $Z = 4.32$, $P < .0001$). Based on these data, the typical radiologist must currently interpret one image every 3–4 seconds over the span of an 8-hour workday to satisfy workload demands.

DISCUSSION

The results from our large single-center radiology practice revealed that, despite efforts to normalize staffing workload for increases in cross-sectional imaging utilization, radiologist workloads are dramatically increasing. Although there has been a steady rise in the number of examinations performed per year, much of this increase in workload burden is a result of increases in the number of images that must be interpreted in each examination. Increases in examination content alone have increased the workload of the radiologist between fourfold to sevenfold. Among examination types, diagnostic CT and MRI studies have experienced the greatest increases in utilization and are predominantly responsible for these observed workload increases, particularly within neuro, body, and chest radiology subspecialties. The clinical impact of these increasing workloads on radiologists remains undefined but may at some point compromise diagnostic accuracy and, in turn, the quality of health care delivery.

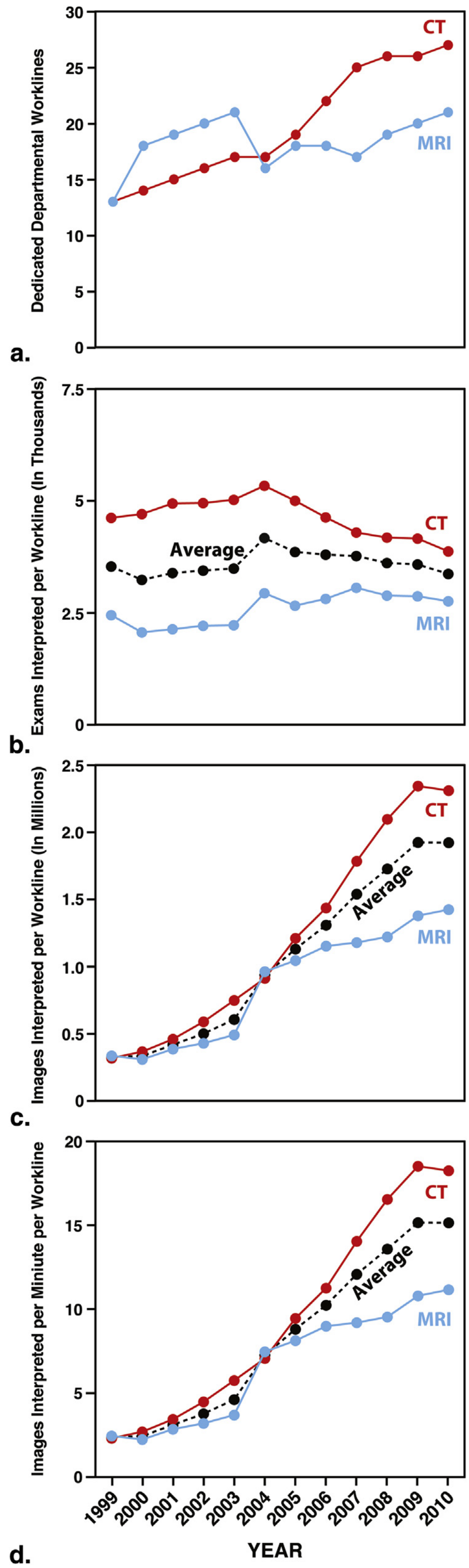


Figure 3. Effect of imaging utilization and examination content on radiologist workload. Trends in numbers of departmental CT and MRI worklines **(a)**, examinations interpreted per workline **(b)**, images interpreted per workline **(c)**, and images interpreted per minute per workline normalized to a 255-day workyear and an 8-hour workday **(d)**. CT data are shown as *blue lines* and MRI data are shown as *red lines*. Average numbers of examinations and images interpreted per workline and images interpreted per minute during a workday are shown as a *black dashed line*. CT, computed tomography; MRI, magnetic resonance imaging. (Color version of figure is available online.)

Recent increases in imaging utilization are well documented in the medical literature (4,16,34–41). Cross-sectional imaging utilization at our institution increased by 68% for CT examinations and 85% for MRI examinations over a 12-year period from 1999 to 2010. These observed changes in CT utilization are consistent with the changes reported by Boone et al. at the UC Davis Medical Campus (48% increase between 2000 and 2004) but less than the changes reported by Korley et al. at the John's Hopkins University Medical Campus (300% increase between 1998 and 2007) (4,34). As these studies were conducted during the same period at other large tertiary care facilities, utilization changes should reflect similar changes in clinical guidelines and technological innovations that are unrelated to regional differences in patient referrals or practice patterns. Practice data from our institution demonstrate that increases in CT and MRI utilization have been offset via departmental staffing increases that have kept the number of interpreted examinations per radiologist fairly constant over the study interval.

Unlike prior studies that sought to examine patient-normalized changes in utilization, our study sought to determine how changes in utilization, clinical use, and technological advances manifested as changes in overall workload. Our results demonstrated a 1300% increase in CT examination image content and a 540% increase in MRI examination image content over the study interval that translated to a sevenfold and fourfold increase in radiologist workload for daily assigned worklines in CT and MRI, respectively. These results demonstrate that increases in information content within each examination (eg, number of images/exam) play a larger role than increases in CT and MRI utilization in the increasing workload of the practicing radiologist.

During this period, several factors were likely responsible for the observed increases in utilization. First, our study time frame spans a transition period in evidence-based medical practice where the examination performance of CT and MRI in the detection of disease has been shown to be superior to conventional radiographs (4,13,16,17,40). In response to this evidence, providers in the emergent, inpatient, and outpatient setting now routinely order CT and MRI studies in lieu of conventional radiographs (4,37). Second, the technological advances have increased the speed in which both CT and MRI examinations can be performed. Such increases in speed have promoted increased use of CT and MRI modalities in a high-throughput model of health care delivery in the emergent and urgent care setting (2,22). Third, increases in imaging speed and other technological advancements have led to the development of new imaging applications such as electrocardiography-gated CT examinations of the heart, CT, and MR enterography (5,9,22,42).

Fourth, the medicolegal ramifications of overlooking seemingly benign patient presentations have driven providers to use cross-sectional imaging as a defensive tool for a wide spectrum of clinical complaints and presentations (43). This practice pattern now pervades urgent care and emergency room settings where CT and MRI examinations are now routinely ordered on most patients, often without regard to the Bayesian probabilities of disease given the patients' presenting symptoms and demographic characteristics (43).

The causes of increased imaging volumes are likely due to several phenomena. First, the past 20 years has been associated with marked technological advancements in CT and MR imaging. CT scanners, now in their fifth generation of design, have seen advances in detector technology, source-detector geometries, computing power needed to perform multiple multiplanar image reconstructions, and overall design that now permit more rapid acquisition of studies that are much higher in anatomic resolution when compared to studies in the 1990s (5). Similarly, MR scanners have also benefitted from recent advances in active shielding, higher field strengths, new pulse sequences, and implementation of parallel imaging techniques that now permit acquisition of both higher anatomic resolution images and, as a result of more favorable signal-to-noise scanner performance, a greater number of images that can be collected in the same period (22). These advances, in both acquisition time and resolution, have led to development and implementation of newer imaging techniques that serve to broaden the clinical utility of CT and MRI in the detection of pathology (5,18,22,37). Collectively, such advances have led to greater imaging volumes, as examination data sets can now contain several thousand images because of their anatomic resolution and complexity of study parameters.

Our study has several limitations. First, as our analysis was limited to a CT and MRI modalities, our estimates of radiologist workload may have been slightly overestimated because of compensatory declines in radiograph and other imaging modality volumes that were not included in this study. However, as the majority of the image volumes in radiology are generated from CT and MR imaging, the potential for significant overestimation is minimal. Second, our department converted to an all-electronic filmless PACS environment during the study interval, and the increases in efficiency these systems confer are not considered in this study. However, as utilization and information content continue to increase even after implementation of more efficient PACS systems, workloads are still expected to increase. Third, as our study was based on database searches alone, source images, stored thin-section, and multiplanar reformatted images were also included in our analysis. However, as radiologists are still legally responsible for interpreting all of the information content contained within an examination, often even source images must be interpreted to detect subtle anomalies that are absent from the aggregated maximum intensity projections or other reformatted images. Furthermore, as our institution is somewhat unique insofar as reconstructed images are generated before the data are sent to PACS and are not generated by the radiologist from a primary "thin-section" data set, the number of images from each examination is an accurate representation of the number of images from the various multiplanar and reconstruction kernels derived from this primary data that are directly used in the interpretation of the study. Fourth, although our study assumes that workload is primarily driven by imaging volumes alone and the time associated with interpreting these images, it remains possible that radiologists have compensated for these dramatic increases in examination image content by spending even less time viewing each image than what our findings suggest. However, as studies have shown that efficiency and accuracy of interpretation declines with increasing fatigue, there is likely a finite limit to the number of images that a radiologist can confidently interpret in any day before patient safety is compromised (28,29). These limits are poorly quantified and unfortunately beyond the scope of this study.

In conclusion, our findings suggest that increases in radiologist workload over the last decade are driven more by increases in image content within each CT and MRI examination than increased utilization of CT and MRI. Although staffing changes have adapted to compensate for increases in CT and MRI examination utilization, to date, there has been little done to mitigate the impact of increases in imaging content on workload. The effect of increased examination image content on fatigue and interpretation accuracy remains a relatively undefined clinical problem and merits additional investigation.

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